Indian J. Phys. **49**, 939–943 (1975)

Electron mobility in (0,0,0) valley of GaSb at very low temperature

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(*Received* 31 *May* 1975)

The mobility of electrons in the (0, 0, 0) valley of n-GaSb has been calculated. The results have been compared with available experimental data. The agreement is quite satisfactory

1. INTRODUCTION

Electron mobility in n-GaSb at very low temperature (~ 4.2 °K) is very interesting. GaSb is one of those polar semiconductors with a small effective charge and so the effect of polar optical scattering is insignificant in charge transport processes. At the above mentioned temperature region we can altogether neglect electron-phonon scattering and take into consideration scattering by ionized impurities alone. The usual practice is to take a screened Coulomb potential as the scattering potential This leads to the familiar Brooks-Herring formula (1955). The scattering potential $V(q)$ in such a case, i.e. for an ion embedded in a dielectric medium, is given in wave number space as

$$V(q) = V_{ion}(q)\, \epsilon(q)^{-1}, \tag{1}$$

with

$V_{ion}(q)$, the potential due to a free ion. given as

$$V_{ion}(q) = -\frac{4\pi e^2}{\epsilon_0} q^{-2} \tag{2}$$

and $\epsilon(q)$ is the Lindhard (1964) dielectric function

Eisenberg & Unger (1974) have derived the linear dielectric function for a free electron gas with arbitrary degeneracy using a density matrix method. They have thus generalized the Lindhard dielectric function as given by

$$\epsilon(q) = 1 + \frac{\lambda^2}{q^2}, \tag{3}$$

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where λ^{-1} is the screening length and $\phi(q)$ is the so-called Filter-function (Eisenberg & Unger 1974)

$$\phi(q) = \frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\beta^{\frac{1}{2}}qF_{-\frac{1}{2}}(x)} \int_0^\infty \frac{1}{1+\exp(y-x)} \log \frac{|q+2^{3/2}x^{1/2}\beta^{-1/2}|}{|q-2^{3/2}x^{1/2}\beta^{-1/2}|} dy \quad \ldots \quad (4)$$

In eq (4)

$$\beta = \frac{1}{k_B T}, \quad x = \beta E_F, \quad y = \beta E$$

and

$$F_n(x) = \frac{1}{\Gamma(n+1)} \int_0^\infty \frac{y^n}{1+\exp(y-x)} dy$$

2. Calculation of Relaxation Time

Relaxation time is calculated by using the following standard formula

$$\frac{1}{\tau} = \frac{2\pi N_i \hbar K}{m} \int_0^\pi \sigma(\theta)(1-\cos\theta)\sin\theta \, d\theta, \quad \ldots \quad (5)$$

where N_i = density of ionized impurities, and $\sigma(\theta)$ = differential scattering crosssection and is given by

$$\sigma(\theta) = \frac{m^2}{4\pi^2\hbar^4} |V(q)|^2, \quad \ldots \quad (6)$$

Putting this value of $\sigma(\theta)$ in eq. (5) and using the relation

$$q^2 = 4K^2 \sin^2 \theta/2,$$

we get

$$\frac{1}{\tau} = \frac{2\pi N_i m e^4}{\epsilon_0^2 \hbar^3 K^3} \int_0^{q^2=4k^2} \frac{q^2 dq^2}{(q^2+\lambda^2\phi)^2}. \quad \ldots \quad (7)$$

In the low-field limit $\phi(q)$ may be approximated as (Eisenberg 1974),

$$\phi(q) = \frac{1}{1+C^2q^2} \quad \ldots \quad (8)$$

where

$$C^2 = \frac{\beta}{12} \frac{\hbar^2}{m} \frac{F_{-3/2}(x)}{F_{-\frac{1}{2}}(x)}. \quad \ldots \quad (9)$$

Under this approximation the integral in eq. (7) can be evaluated analytically We thus obtain

$$\frac{1}{\tau} = \frac{2\pi N_i m e^4}{\epsilon_0^2 \hbar^3 K^3} Q \quad \ldots \quad (10)$$

where

$$Q = \tfrac{1}{2}\log\left\{1+\frac{4K^2}{\lambda^2}(1+4C^2K^2)\right\}$$

$$+\frac{1-2C^2\lambda^2}{1-C^2\lambda^2)^{3/2}}\,\tfrac{1}{2}\log\left\{\frac{1+\dfrac{2K^2}{\lambda^2}(1+\sqrt{1-4C^2\lambda^2})}{1+\dfrac{2K^2}{\lambda^2}(1-\sqrt{1-4C^2\lambda^2})}\right\}$$

$$-\frac{4K^2(1+4C^2K^2-3C^2\lambda^2-8C^2K^2\lambda^2)}{(1-4C^2\lambda^2)(\lambda^2+4K^2+16C^2K^4)} \quad \ldots \quad (11)$$

In the high temperature limit $c \to 0$, and the above expression reduces to the well-known Brooks-Herring (1955) formula

$$\frac{1}{\tau} = \frac{2\pi N_i m e^4}{c_0{}^2\hbar^3K^3}\left[\log\left(1+\frac{4K^2}{\lambda^2}\right)-\frac{4K^2/\lambda^2}{1+\dfrac{4K^2}{\lambda^2}}\right] \quad \ldots \quad (12)$$

Once the relaxation time is known mobility can be calculated by the formula

$$\mu = \frac{e}{m} < \tau(E) >.$$

In the case of degenerate semiconductors the mobility involves the relaxation time τ of the electrons at the Fermi energy (Shockley 1950), so that

$$\mu_{deg} = \frac{e}{m}\tau(E_F). \quad \ldots \quad (13)$$

3. Application to n-GaSb

For highly degenerate n-GaSb, N_i is the sum of the compensated acceptors N_0 and the total number of electrons n in both the $\Gamma(0, 0, 0)$ and $L(1, 1, 1)$ valleys :

$$N_i = N_0+n$$

It is well-known that

$$n = n_1+n_2$$

$$= \frac{8\pi}{3}\left(\frac{2m_{1d}}{h^2}\right)^{3/2} E_{F_1}{}^{3/2}+\frac{8\pi}{3}\left(\frac{2m_{2d}}{h^2}\right)^{3/2}E_{F_2}{}^{3/2} \quad \ldots \quad (14)$$

In the above expression m_{1d}, m_{2d} are the density-of-states effective mass in Γ and L valleys respectively. E_{F_1}, E_{F_2} are the corresponding Fermi levels which are connected by the relation

$$E_{F_2} = E_{F_1}-\Delta E$$

where ΔE is the energy gap between the two valleys.

We shall consider screening to be due to electrons in both the valleys so that λ^2 is given by (Robert & Barjon 1970)

$$\lambda^2 = \frac{6\pi e^2}{\epsilon_0}\left(\frac{n_1}{E_{F_1}} + \frac{n_2}{E_{F_2}}\right)$$

4. Results and Discussions

For the sake of comparison with other workers (Robert & Barjon 1970, Harland & Woolley 1966) we have evaluated from eq (13) the mobility ratio

$$\frac{\mu_1}{\mu_{1c}} = \left(\frac{E_{F1}}{E_{F1c}}\right)^{3/2} \cdot \frac{N_{1c}}{N_1} \cdot \frac{Q_{1c}}{Q_1} \qquad \ldots \quad (15)$$

where the suffix 1 denotes the quantities in the Γ valley and the suffix c denotes the corresponding quantities in the case the Fermi level touches the bottom of the L valley.

In calculating the mobility ratio we have used the following data of Robert & Barjon (1970) :

$$m_{1d} = 0.048\ m_0 \qquad \epsilon_0 = 16$$
$$m_{2d} = 0\ 24\ m_0 \qquad N_0 = 10^{17}\ \mathrm{cm}^{-3}$$
$$\Delta E = 77\ \mathrm{meV}$$

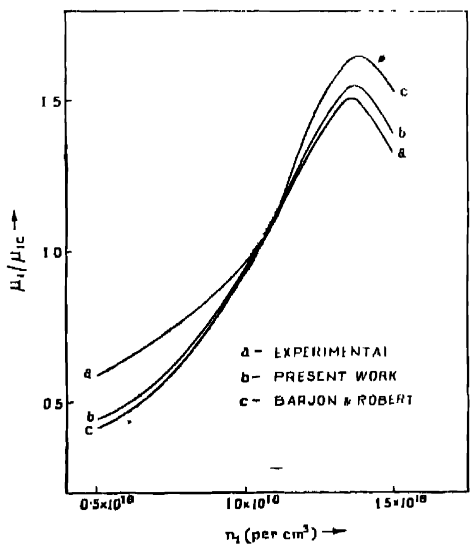

Fig. 1. Mobility ratio μ_1/μ_{1c} plotted against the concentration of electrons n_1 in the Γ

We have plotted in figure 1 the calculated mobility ratio μ_1/μ_{1c} against carrier concentration n_1 in Γ valley together with the experimental data of Harland & Wooley (1966) and the theoretical results of Robert & Barjon (1970) Our results show very close agreement with experimental values at concentrations above 10^{18} cm^{-3} However, it is clear from figure 1 that at all values of n_1 considered by Robert & Barjon (1970) and the present authors, the results obtained by the latter are definitely in better agreement with the experimental results of Harland & Woolley (1966)

Acknowledgment

The authors would like to thank Professor P C Bhattacharya, Head of the Department of Physics, for his interest in this work Our thanks are due also to Mr. D Ghosh and Mr. T. R. Bose for discussions

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